



Faculty Of Engineering

**IMPACT BEHAVIOUR OF BIO-INSPIRED SANDWICH BEAM
WITH VARYING CORE GEOMETRIES**

Siaw Yang Yew (57857)

**Bachelor of Engineering with Honors
(Civil Engineering)
2020**

UNIVERSITI MALAYSIA SARAWAK

Grade: _____

Please tick (✓)

Final Year Project Report

☒

Masters

☐

PhD

☐

DECLARATION OF ORIGINAL WORK

This declaration is made on the 10th AUGUST 2020.

Student's Declaration:

I, SIAW YANG YEW from FACULTY OF ENGINEERING hereby declare that the work entitled, IMPACT BEHAVIOUR OF BIO-INSPIRED SANDWICH BEAM WITH VARYING CORE GEOMETRIES is my original work. I have not copied from any other sources except where due reference or acknowledgement is made explicitly in the text, nor has any part been written for me by another person.

10th AUGUST 2020

Date submitted



SIAW YANG YEW (57857)

Supervisor's Declaration:

I, ASSOCIATE PROFESSOR DR AHMAD KUEH BENG HONG hereby certifies that the work entitled, IMPACT BEHAVIOUR OF BIO-INSPIRED SANDWICH BEAM WITH VARYING CORE GEOMETRIES was prepared by the above named student, and was submitted to the "FACULTY" as a partial KNS 4254 Final Year Project fulfilment for the conferment of BACHELOR OF ENGINEERING WITH HONOURS (CIVIL ENGINEERING), and the aforementioned work, to the best of my knowledge, is the best student's work.

Received for examination by:



(ASSOCIATE PROFESSOR DR AHMAD KUEH BENG HONG)

Date: 10th AUGUST 2020

I declare this Project /Thesis is classified as (Please tick (✓)):

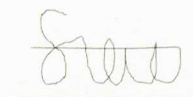
- ☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- ☐ **RESTRICTED** (Contains restricted information as specified by the organisation where research was done) *
- ☒ **OPEN ACCESS**

Validation of Project/Thesis

I therefore duly affirmed with free consent and willingness declared that this said Project/Thesis shall be placed officially in the Centre for Academic Information Services with the abide interest and rights as follows:

- This Project/Thesis is the sole legal property of Universiti Malaysia Sarawak (UNIMAS).
- The Centre for Academic Information Services has the lawful right to make copies for the purpose of academic and research only and not for other purpose.
- The Centre for Academic Information Services has the lawful right to digitise the content to for the Local Content Database.
- The Centre for Academic Information Services has the lawful right to make copies of the Project/Thesis for academic exchange between Higher Learning Institute.
- No dispute or any claim shall arise from the student itself neither third party on this Project/Thesis once it becomes sole property of UNIMAS.
- This Project/Thesis or any material, data and information related to it shall not be distributed, published or disclosed to any party by the student except with UNIMAS permission.

Student's signature:



(10th AUGUST 2020)

Supervisor's signature:



(10th AUGUST 2020)

Current Address:

DEPT. OF CIVIL ENGINEERING, FACULTY OF ENGINEERING, 94300 KOTA SAMARAHAN, SARAWAK

Notes: * If the Report is **CONFIDENTIAL** or **RESTRICTED**, please attach together as annexure a letter from the organisation with the period and reasons of confidentiality and restriction.

The following Final Year Project Report:

ACKNOWLEDGEMENTS

Title : Impact Behaviour of Bio-Inspired Sandwich Beam with Varying Core Geometries

Name : Siaw Yang Yew

Matric No. : 57857

has been read and approved by:



(Associate Professor Dr. Ahmad Kueh Beng Hong)

Project Supervisor

10th August 2020

Date

ACKNOWLEDGEMENTS

First and foremost, I would like to express my special thanks of gratitude to my supervisor, Associate Professor Dr Ahmad Kueh Beng Hong and my co-supervisors, Mr Abd Azim Abdullah and Dr Raudhah Ahmadi for providing invaluable guidance, comments and suggestions in completing my graduate study. I felt very grateful to have such excellent and helpful supervisor and co-supervisors. Their technical advice and support are essential to the completion of my graduate study.

Secondly, I am extremely grateful to my parents and members of my family for their financial support, moral supports and encouragement in completing my graduate studies.

Thirdly, I am extremely thankful to my friends especially Tan Juin Hwee and Tan Chun Yean for their continuous assistance, encouragements and supports throughout my graduate study.

ABSTRACT

Impact resistance efficiencies of the bio-inspired sandwich beam (BHSB) with varying solid hot melt adhesive (HMA) hyoid core thicknesses and leg spans were examined under the impact energy of 7.28J at the mid-span of the sandwich beam. The sandwich beam models consist of dual-core comprising solid hot melt adhesive (HMA) and aluminum honeycomb cores sandwiched between the top and bottom carbon fiber reinforced plastic (CFRP) skins. The HMA core was designed with an arch shape. Considered HMA hyoid thicknesses include 3 mm, 4.574 mm, and 10 mm with various leg spans of 10 mm, 25 mm, and 35 mm. The finite element software, ABAQUS, was used to construct the BHSB models in examining the impact behaviors of these models. Assessed performances include displacement-time, velocity-time, acceleration-time, impact energy-time, and stress contour distribution. Then, the impact resistance efficiency index was used to determine the overall performance of all the BHSB models. In conclusion, the BHSB with HMA hyoid thickness of 4.574 mm and a hyoid leg span of 10 mm is the most superior in terms of impact resistance efficiency index among all the proposed sandwich beam models as it has the highest impact resistance efficiency index of 25.53.

ABSTRAK

Kecekapan ketahanan hentaman bagi “Bio-inspired sandwich beam” (BHSB) dengan ketebalan “Solid Hot Melt Adhesive (HMA) hyoid core” yang berbeza-beza dan jarak kaki yang berbeza-beza diperiksa di bawah tenaga hentaman dengan “7.28J” di tengah BHSB. BHSB mengandungi dua lapisan terdiri daripada “solid hot melt adhesive (HMA) core” dan “aluminium honeycomb core” yang dilekat di antara kulit atas dan bawah yang dibuat daripada “carbon fiber reinforced plastic” (CFRP). “HMA hyoid” direka bentuk dalam bentuk lengkungan. Dalam kajian ini, ketebalan “HMA hyoid” yang dipertimbangkan merangkumi 3 mm, 4.574 mm dan 10 mm dengan pelbagai jarak kaki iaitu 10 mm, 25 mm dan 35 mm. Perisian elemen aplikasi, ABAQUS digunakan untuk membina “BHSB” model untuk mengkaji tingkah laku impak bagi “BHSB” model. Prestasi yang dinilai merangkumi masa perpindahan, masa halaju, masa pecutan, masa tenaga impak, dan taburan kontur tekanan. Kemudian, indeks kecekapan rintangan hentaman digunakan untuk menentukan prestasi keseluruhan bagi semua “BHSB” model. Kesimpulannya, “BHSB” dengan 4.574 mm ketebalan “HMA hyoid” dan 10mm jarak kaki “HMA hyoid” adalah yang paling unggul dari segi indeks kecekapan ketahanan hentaman di antara semua “BHSB” yang dicadangkan kerana dia mempunyai indeks kecekapan ketahanan hentaman yang paling tinggi iaitu 25.53.

TABLE OF CONTENT

ACKNOWLEDGEMENTS	i
ABSTRACT	ii
ABSTRAK	iii
TABLE OF CONTENT	iv
LIST OF FIGURES	vii
LIST OF TABLES	xiii
LIST OF SYMBOLS.....	xiv
CHAPTER 1: INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statement	5
1.3 Aims and Objectives	6
1.4 Scope of Study	6
1.5 Significance of study	7
CHAPTER 2: LITERATURE REVIEW	8
2.1 Introduction.....	8
2.2 Influence of the Curving Angle on Impact Performance of Sandwich Beam.	8
2.3 Effect of Different Core Thickness on Sandwich Structure	11
2.4 Effect of Varying Thickness of Flat face plate and spacing of two adjoining core plates for Sandwich Structure with Web core.....	20
2.5 Influence of Varying Core Length and Cell Wall Thickness of Sandwich Structure Consisting Trapezoidal Corrugated Core	27
2.6 Influence of Thickness for Core and Number of Intermediate Core Layers for Polypropylene Honeycomb Multi-layer Sandwich Structures.	30
2.7 Concluding remarks.....	33

CHAPTER 3: METHODOLOGY	34
3.1 Introduction.....	34
3.2 Development of bio-inspired dual-core sandwich beam	35
3.3 Finite Element Modelling	36
3.4 Leg Angle and Leg Span for Hyoid Core	37
3.5 Geometry and Material Description.....	39
3.6 Model Construction	42
3.6.1 CFRP skins.....	43
3.6.2 Honeycomb Core	46
3.6.3 Arch shaped core (Hyoid)	48
3.6.4 Impactor	51
3.6.5 Surface Assignment	55
3.6.6 Properties and section manager	56
3.6.8 Step Module	70
3.6.9 Interaction	75
3.6.10 Boundary Condition and Impact Velocity	79
3.6.11 Meshing.....	83
3.6.12 Running the model analysis	86
3.7 Convergence Study	88
CHAPTER 4: RESULTS AND DISCUSSION	93
4.1 Introduction.....	93
4.2 Impact resistance.....	93
4.3 Stress propagation.....	96
4.4 Sandwich beam failure modes	109
4.5 Displacement, Velocity and Acceleration Histories of impactor.....	116

4.6 Absorbed Energy	121
4.7 Impact Resistance Efficiency Index.....	125
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS.....	133
5.1 Conclusion	133
5.2 Recommendations.....	134
REFERENCE:	136

LIST OF FIGURES

<i>Figure 1.1.</i> Loadings carried by face and core of sandwich structure (Campbell, 2010).	1
<i>Figure 1.2.</i> Failure modes of sandwich structure under low-velocity impact (Sabah, Kueh and Bunnori, 2019).....	3
<i>Figure 1.3.</i> a) Head configuration of woodpecker and b) Bioinspired sandwich beam with honeycomb core (Sabah, Kueh and Al-Fasih, 2018).....	4
<i>Figure 2.1.</i> Curved sandwich beam (Baba, 2013).....	9
<i>Figure 2.2.</i> Graph of contact force against time for different curvature angle with no debond (Baba, 2013)	10
<i>Figure 2.3.</i> Graph showing relationship between displacement and time for different curvature angle with no debond (Baba, 2013).....	11
<i>Figure 2.4.</i> Processes to produce the sandwich panel (Ozdemir et al., 2018).....	12
<i>Figure 2.5.</i> a) Graph of showing relation of contact force and deformation and b) Graph of showing relation of energy and time for 15 mm core thick balsa wood when it is subjected to single impact events (Ozdemir et al., 2018).....	13
<i>Figure 2.6.</i> a) Graph of showing relation of contact force and deformation and b) Graph of showing relation of energy and time for 25 mm core thick balsa wood when it is subjected to single impact events (Ozdemir et al., 2018).....	13
<i>Figure 2.7.</i> Graph of absorbed energy against impact energy for 15 mm and 25 mm core thickness (Ozdemir et al., 2018).....	14
<i>Figure 2.8.</i> Contact force-deformation curve and b) energy-time curve for 15 mm thick core sandwich composites when subjected to 10J repeated impact loading (Ozdemir et al., 2018).....	15
<i>Figure 2.9.</i> Contact force-deformation curve and b) energy-time curve for 15 mm thick core sandwich composites when subjected to 25J repeated impact loading (Ozdemir et al., 2018).....	15
<i>Figure 2.10.</i> Top and rear surface of the sandwich composite with core thickness of a)15 mm and b) 25 mm under 80J impact energy (Ozdemir et al., 2018).....	16
<i>Figure 2.11.</i> top and rear surface of the sandwich composite with core thickness of a)15 mm and b) 25 mm under 10J impact energy (Ozdemir et al., 2018).....	17

<i>Figure 2.12.</i> Effect of different drop height on the maximum impact force and damage area for 20 mm thick core (Sawal et al.,2011).	18
<i>Figure 2.13.</i> Effect of different drop height on the maximum impact force and damage area for 30 mm thick core (Sawal et al., 2011).	19
<i>Figure 2.14.</i> Effect of different drop height on the maximum impact force and damage area for 40 mm thick core (Sawal et al.,2011).	19
<i>Figure 2.15.</i> Over-hanging three points bending testing (Jiang et al., 2017).....	20
<i>Figure 2.16.</i> Sandwich plate with web core (Jiang et al., 2017).	21
<i>Figure 2.17.</i> Graph of load against deflection of sandwich plate (Jiang et al., 2017).....	22
<i>Figure 2.18.</i> Graph of load against deflection for experimental data and FEM (Jiang et al., 2017).....	22
<i>Figure 2.19.</i> Graph of load against deflection for different thickness of face plate (Jiang et al., 2017).....	23
<i>Figure 2.20.</i> Graph of shear stiffness against face-plate thickness (Jiang et al., 2017),.....	24
<i>Figure 2.21.</i> Graph of load versus deflection for web-core sandwich with same h_s and diverse s (Jiang et al., 2017).	25
<i>Figure 2.22.</i> Bending and shear stiffness of web-core sandwich with varying core height and spacing between two core plates (Jiang et al., 2017).....	26
<i>Figure 2.23.</i> Compression test (Zaid et al., 2016).....	27
<i>Figure 2.24.</i> Graph of compression stress against number of unit cells for GF3P and CF5P (Zaid et al., 2016).	29
<i>Figure 2.25.</i> Graph of compression stress against wall of thickness for GF3U and CF3U (Zaid et al., 2016)	29
<i>Figure 2.26.</i> Typical load-bending curve for 10 mm, 20 mm and 40 mm core (Arbaoui et al., 2014).....	30
<i>Figure 2.27.</i> Indentation, debonding and buckling of the sandwich structure (Arbaoui et al. 2014).....	31
<i>Figure 2.28.</i> Graph of load against bending plotted under static three-points bending with support span, $L=300$ mm of the multilayer sandwich (40 mm) (Arbaoui et al. 2014).....	32
<i>Figure 3.1.</i> Bio-inspired dual-core sandwich beam model.	35
<i>Figure 3.2.</i> Flow chart of showing the procedure to produce model in ABAQUS.....	36

<i>Figure 3.3. Core configuration of bio-inspired sandwich with 36° arch hyoid leg.</i>	37
<i>Figure 3.4. Parabolic curve for hyoid leg span of 10 mm.</i>	38
<i>Figure 3.5. Parabolic curve for hyoid leg span of 25 mm.</i>	38
<i>Figure 3.6. Parabolic curve for hyoid leg span of 35 mm.</i>	39
<i>Figure 3.7. Stress-strain curve of HMA.</i>	41
<i>Figure 3.8. Bio-inspired dual-core sandwich beam.</i>	42
<i>Figure 3.9. 'Create Part' dialog box.</i>	44
<i>Figure 3.10. Sketcher viewport.</i>	44
<i>Figure 3.11. Partition from Tools at main menu.</i>	45
<i>Figure 3.12. 'Create partition' dialog and the partition of CFRPT.</i>	45
<i>Figure 3.13. Copy of CFRPB from CFRPT.</i>	46
<i>Figure 3.14. Single cell of honeycomb core.</i>	47
<i>Figure 3.15. "Translate" in the "Edit".</i>	47
<i>Figure 3.16. Cell arrangement for honeycomb core.</i>	48
<i>Figure 3.17. Honeycomb core with 20mm depth.</i>	48
<i>Figure 3.18. Cross-section of hyoid.</i>	49
<i>Figure 3.19. Selected face of rectangular hollow section.</i>	50
<i>Figure 3.20. The arc lines drawn using "Create Arc: Thru 3 points".</i>	50
<i>Figure 3.21. The trimmed arc lines.</i>	50
<i>Figure 3.22: Extruded rectangular hollow section.</i>	51
<i>Figure 3.23. Circle with radius of 6 mm and "Edit Base Extrusion.</i>	51
<i>Figure 3.24. The 3D cylinder layer.</i>	52
<i>Figure 3.25: The drawn quadrant and the data used in "Edit Evolution" dialog box.</i>	52
<i>Figure 3.26. The completed hemisphere layer.</i>	53
<i>Figure 3.27. Separated cylinder and hemisphere layers.</i>	53
<i>Figure 3.28. Assembly together the cylinder and hemisphere.</i>	54
<i>Figure 3.29. Merging process of impactor.</i>	54
<i>Figure 3.30. Creating surface.</i>	55
<i>Figure 3.31. Selecting the CFRP top skin.</i>	55
<i>Figure 3.32. Defined top and bottom surface of CFRP top skin.</i>	56
<i>Figure 3.33. Material behaviors of HMA: (a) Density and elastic; (b) Plastic.</i>	59

<i>Figure 3.34. Material behaviors of impactor and CFRP</i>	<i>60</i>
<i>Figure 3.35. Material behaviors of aluminium honeycomb core.</i>	<i>60</i>
<i>Figure 3.36. Input of inertia and selected reference point.....</i>	<i>61</i>
<i>Figure 3.37. “Create section” dialog box.</i>	<i>62</i>
<i>Figure 3.38. Information inserted in “Edit Section” dialog box</i>	<i>62</i>
<i>Figure 3.39. Selecting whole hyoid for assignation of section.</i>	<i>63</i>
<i>Figure 3.40. Information inserted in “Edit Section Assignment” dialog box.</i>	<i>63</i>
<i>Figure 3.41. Stacking sequence of skin (Sabah, Kueh, and Al-Fasih, 2018).....</i>	<i>64</i>
<i>Figure 3.42. Section for CFRP top skin.</i>	<i>64</i>
<i>Figure 3.43. Section for CFRP bottom skin.</i>	<i>65</i>
<i>Figure 3.44. Section for Impactor.</i>	<i>65</i>
<i>Figure 3.45. Section for aluminium honeycomb core.....</i>	<i>66</i>
<i>Figure 3.46. Section assignment for Hyoid.....</i>	<i>67</i>
<i>Figure 3.47. Selection of CFRPT and Impactor from the “Create Instance” dialog box....</i>	<i>68</i>
<i>Figure 3.48. Reference point RP-1 and RP-2.....</i>	<i>68</i>
<i>Figure 3.49. Assembly of CFRP-T and impactor.</i>	<i>69</i>
<i>Figure 3.50. Assembly of the sandwich beam.</i>	<i>70</i>
<i>Figure 3.51. Spacing between model instances.</i>	<i>70</i>
<i>Figure 3.52. Create Step and Edit Step dialog boxes.....</i>	<i>71</i>
<i>Figure 3.53. Field output 1.....</i>	<i>73</i>
<i>Figure 3.54. First History Output.....</i>	<i>74</i>
<i>Figure 3.55. Second and third History Output.</i>	<i>74</i>
<i>Figure 3.56. Fourth and fifth History Output.....</i>	<i>75</i>
<i>Figure 3.57. Interaction between impactor and CFRP top skin.</i>	<i>76</i>
<i>Figure 3.58. Interaction property.</i>	<i>77</i>
<i>Figure 3.59. Contact property options.</i>	<i>77</i>
<i>Figure 3.60. Tie constraint between top skin and HMA (Hyoid).</i>	<i>78</i>
<i>Figure 3.61. “Create Boundary Condition” dialog box.....</i>	<i>79</i>
<i>Figure 3.62. Boundary condition of Aluminium Honeycomb core.</i>	<i>80</i>
<i>Figure 3.63. Boundary condition of “CFRP-T EDGES”.</i>	<i>80</i>
<i>Figure 3.64. Boundary condition of “CFRPB”.</i>	<i>81</i>

<i>Figure 3.65. Boundary condition of “HYOID SIDES”.</i>	81
<i>Figure 3.66. Boundary condition of Impactor.</i>	82
<i>Figure 3.67. Predefined field for impactor.</i>	82
<i>Figure 3.68. Creating global seeds of CFRP skins.</i>	83
<i>Figure 3.69. Seed edges for CFRP skins.</i>	84
<i>Figure 3.70. Complete mesh of CFRP skins.</i>	84
<i>Figure 3.71. Element size used at different regions of hyoid.</i>	85
<i>Figure 3.72. 3-node triangular element type for arch regions of hyoid.</i>	85
<i>Figure 3.73. Creating job.</i>	86
<i>Figure 3.74. Job manager.</i>	87
<i>Figure 3.75. Visualisation of sandwich beam models.</i>	87
<i>Figure 3.76. Graph of displacement against 1/element size for 3 mm thick hyoid.</i>	88
<i>Figure 3.77. Graph of displacement against 1/element size for 4.574 mm thick hyoid.</i>	89
<i>Figure 3.78. Graph of displacement against 1/element size for 10 mm thick hyoid.</i>	89
<i>Figure 4.1. Graph of contact force against time for 10 mm leg span with varying thickness.</i>	94
<i>Figure 4.2. Graph of contact force against time for 25 mm leg span with varying thickness.</i>	94
<i>Figure 4.3. Graph of contact force against time for 35 mm leg span with varying thickness.</i>	95
<i>Figure 4.4. Graph of maximum stress against thickness for hyoid leg span of 10 mm.</i>	97
<i>Figure 4.5. Graph of maximum stress against thickness for hyoid leg span of 25 mm.</i>	97
<i>Figure 4.6. Graph of maximum stress against thickness for hyoid leg span of 35 mm.</i>	98
<i>Figure 4.7. The distribution of stress for HMA hyoid layer for BHSB with HMA hyoid thickness of 3 mm and leg span of: (a) 10 mm, (b) 25 mm, (c) 35 mm; HMA hyoid thickness of 4.574 mm and leg span of: (d) 10 mm, (e) 25 mm, (f) 35 mm; HMA hyoid thickness of 10mm and leg span of: (g) 10 mm, (h) 25 mm, (i) 35 mm.</i>	103
<i>Figure 4.8. The distribution of stress for bottom CFRP skin for BHSB with HMA hyoid thickness of 3 mm and leg span of: (a) 10 mm, (b) 25 mm, (c) 35 mm; HMA hyoid thickness of 4.574 mm and leg span of: (d) 10 mm, (e) 25 mm, (f) 35 mm; HMA hyoid thickness of 10mm and leg span of: (g) 10 mm, (h) 25 mm, (i) 35 mm.</i>	108

<i>Figure 4.9.</i> (i) Top view, (ii) Side view and (iii) FEM mid-section deformed shape during final deformation after impactor bounces back for HMA hyoid thickness of 3 mm and leg span of: (a) 10 mm, (b) 25 mm, (c) 35 mm; HMA hyoid thickness of 4.574 mm and leg span of: (d) 10 mm, (e) 25 mm, (f) 35 mm; HMA hyoid thickness of 10 mm and leg span of: (g) 10 mm, (h) 25 mm, (i) 35 mm	113
<i>Figure 4.10.</i> Graph of damage area against thickness for HMA hyoid leg span of 10 mm.	114
<i>Figure 4.11.</i> Graph of damage area against thickness for HMA hyoid leg span of 25 mm.	115
<i>Figure 4.12.</i> Graph of damage area against thickness for HMA hyoid leg span of 35 mm.	115
<i>Figure 4.13.</i> Graph of displacement of impactor against time for HMA hyoid thickness of 3 mm, 4.574 mm and 10 mm for (a) leg span = 10 mm (b) leg span = 25 mm and (c) leg span = 35 mm.....	117
<i>Figure 4.14.</i> Graph of velocity of impactor against time for HMA hyoid thickness of 3 mm, 4.574 mm and 10 mm for (a) leg span = 10 mm (b) leg span = 25 mm and (c) leg span = 35 mm	119
<i>Figure 4.15.</i> Graph of acceleration of impactor against time for HMA hyoid thickness of 3 mm, 4.574 mm and 10 mm for (a) leg span = 10 mm (b) leg span = 25 mm and (c) leg span = 35 mm.....	120
<i>Figure 4.16.</i> Graph of energy against time of HMA hyoid thickness of 3 mm, 4.574 mm and 10 mm for (a) leg span = 10 mm, (b) leg span = 25 mm and (c) leg span = 35 mm ...	123
<i>Figure 4.17.</i> Graph of energy absorption (Eabs) against thickness for HMA hyoid leg span of 10 mm, 25 mm and 35 mm	124
<i>Figure 4.18.</i> The bar chart showing the impact resistance efficiency index for all the models which the bottom legend represents leg spans.	132

LIST OF TABLES

Table 2.1. Results of impact test for sandwich beams (Baba, 2013).....	10
Table 2.2. Dimension of sandwich plates with geometrical change (Jiang et al., 2017).....	21
Table 2.3. Compression test variable for corrugated core (Zaid et al., 2016).	28
Table 2.4. Mechanical properties for 10 mm, 20 mm and 30 mm thick core (Arbaoui et al. 2014).....	31
Table 2.5. Mechanical properties of the multilayer sandwich structures with core thickness of 40 mm (Arbaoui et al. 2014).	32
Table 3.1: Thickness of BHSB with different hyoid thickness.	39
Table 3.2. Properties of T350/EP-1006 CFRP (Sabah et al., 2018).	40
Table 3.3. Properties of solid hot melt adhesive (HMA).	40
Table 3.4. Properties of aluminum honeycomb core (Sabah et al., 2019).....	41
Table 3.5. EP-1006 adhesive properties (Sabah et al., 2017).....	41
Table 3.6: The dimensions for the nine models.....	43
Table 3.7. Example of true stress and true strain from Microsoft Excel.....	57
Table 3.8. Convergence study for hyoid thickness = 3 mm for top skin.....	90
Table 3.9. Convergence study for hyoid thickness = 3 mm for bottom skin	90
Table 3.10. Convergence study for hyoid thickness = 4.574 mm	90
Table 3.11. Convergence study for hyoid thickness = 10 mm	90
Table 3.12. Element number for each layers of sandwich beam for 3 mm.	91
Table 3.13. Element number for each layers of sandwich structure for 4.574 mm.....	91
Table 3.14. Element number for each layers of sandwich structure for 10 mm.....	92
Table 4.1. Maximum contact force and the contact time.	96
Table 4.2: Maximum stress for all the models.	98
Table 4.3: The impact resistance efficiency index for all the models.	132

LIST OF SYMBOLS

θ	- Angle of curvature
L_{arc}	- Length of arc
l	- the span
t_f	- Face plate thickness
t_w	- Core plate thickness
L	- Sandwich plate length
B	- Sandwich plate width
H	- Sandwich plate height
h_c	- Height of core plate
s	- Spacing between two adjacent core plates
I_e	- Impact resistance efficiency index
t	- Thickness of sandwich beam

CHAPTER 1

INTRODUCTION

1.1 Research Background

Sandwich structure is defined as the composite structures with multilayer, developed for the expected lifetime loading conditions (Birman and Kardomateas, 2018). Sandwich structure is applied extensively in aerospace field, the beams and columns, refrigerated storage, automobile and shipbuilding industries (Davies, 2001). Sandwich structure is extremely lightweight type of construction with high stiffness, long lasting, high strength and good thermal and sound insulators. Those advantages encourage the wide uses of sandwich structures in the structural application (Zaid et al, 2016). Figure 1.1 shows the loadings carried by skin and core of sandwich structure (Campbell, 2010).

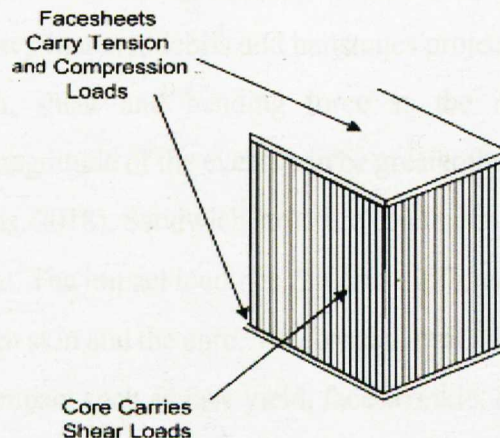


Figure 1.1. Loadings carried by face and core of sandwich structure (Campbell, 2010).

Sandwich structure consists of three parts which two relatively thin stiff and high strength skins are separated by a lightweight thick core which has enough stiffness in direction normal to the skins. Sandwich structure enables design of multi-functional structures which can be achieved by uniting different skins and materials of core (Davies, 2001). The materials of the sandwich structure are chosen based on the usage of the structure, loading, availability and cost (Birman and Kardomateas, 2018). The core can vary in thickness, density and solidity and it occupies small percentage of the sandwich weight. The sandwich structures' structural performance is influenced by the skin properties and the core properties, adhesive connection of the core and the skins and geometrical size of the components (Daniel and Abot, 2000).

The facings are made of steel, aluminium, wood, fibre-reinforced plastic, carbon, aramid and even concrete while the core is made of solid plastic material such as polyethylene, rigid foam material such as polyurethane, polystyrenem and phenolic foam, metal and non-metal honeycombs of metal and non-metal (Davies, 2001). Usually a sandwich structure has relatively thin skin sheets which is ranged from 0.25 to 3 mm while the densities of the core is around 16 to 480kg/m³ (Campbell, 2010). In aerospace applications, the facings of the sandwich structure are typically made of synthetic granite and synthetic carbon while the facings of civil and marine structure are made of glass-epoxy. Aluminum or Nomex honeycomb is used as core for aerospace structures while the closed-cell or open-cell foam are the core used in civil engineering while the ship sandwich structures use balsa with different density as its core (Birman and Kardomateas, 2018).

Sandwich structure can be damaged internally and externally by the impact loads such as bird strike, drop of heavy matters, debris and hailstones projectiles regarding to reduction in tension, compression, shear and bending force as the impact loads will happen instantaneously and the magnitude of the events can be greater than that of its static condition (Birman and Kardomateas, 2018). Sandwich structure can undergo many different modes of failures in an impact event. The impact loadings can cause different modes of damage to skin, core and interface between skin and the core. McCormack et al. (2001) state that some failure during the low velocity impact such as face yield, face wrinkle, core failure and indentation will happen on the sandwich beams as shown in Figure 1.2 as cited in Sabah, Kueh and

Bunnori, 2019. Gibson and Ashby (1997) state that sandwich beam geometry and the materials strength for the core and skin will influence the type of failure as cited in Sabah, Kueh and Bunnori, 2019.

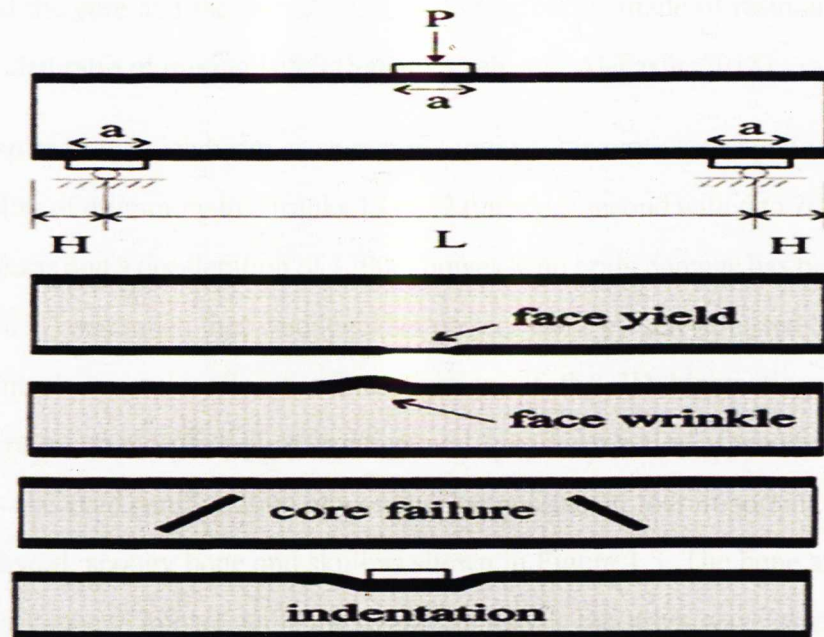


Figure 1.2. Failure modes of sandwich structure under low-velocity impact (Sabah, Kueh and Bunnori, 2019).

Low velocity impact does not able to perforate the structure as the damages are limited to the top skin, but the core will experience shear and slight damage in the bottom skin. The face yield happens when the skin experiences a complete fracture that is caused by the micro-tension. The face wrinkle defines the skin undergo some matrix cracking and fiber breakage because of micro-compression with no fracture (Sabah, Kueh and Bunnori, 2019).

Sandwich structure is good in resisting single impact but the resistance to repeated impact loadings is still not well maximized. Heimbs et al. (2010) as cited in Sabah, Kueh, and Al-Fasih, 2017 stated that sandwich structure with two cores has much higher stiffness and strength than other structures. The combination of two core enhances the resisting power of sandwich structures toward impact. Therefore, bio-inspired honeycomb sandwich beam (BHSB) is introduced. BHSB is made of four layers which the first and last layer was formed by CFRP made of three layers unidirectional T350/EP-1006 which is the first line defense that protects the sandwich structure from impact damage The second layer was the rubber core I with a thickness of 3 mm which spreads and absorbs the impact excitation. The rubber

is used as the core materials as it plays the role to absorb the load in handling the incoming impact force. The third layer was made of aluminium honeycomb core (core II) with cell size of 8 mm, thickness of 20 mm which can suppress any further impact. The EP-1006 adhesive is used to bond the core and the skins. The EP-1006 adhesive made of resin and hardener. The recommended ratio of mixing is 5:3 (Sabah, Kueh, and Al-Fasih, 2018).

Bio-inspired sandwich beam as shown in Figure 1.3 is motivated by the woodpecker with its capability of drumming tree trunks 18 to 22 times per second with 6 to 7m/s repeating high speed impacts and a deceleration of 1200g, however no brain damage has been detected. Wang et al. (2011) examined that woodpeckers protect itself by self-adjusted behavior and special anatomical structure after the investigation of the 3D kinematics, mechanical properties macro/micro morphological structure and dynamic reaction of woodpecker's head quantitatively. The head configuration of woodpecker consists of four important components such as beak, hyoid, spongy bone and skull as shown in Figure 1.3. The bone and beak can increase the resistance to impact while the hyoid can reduce the stress wave essentially from beak to the skull. Besides that, the overall stresses in skull and brain were minimized which is safe. The beak, hyoid, spongy bone and skull of a woodpecker are representing CFRP, rubber core, aluminium honeycomb core and another CFRP respectively (Sabah, Kueh and Al-Fasih, 2018).

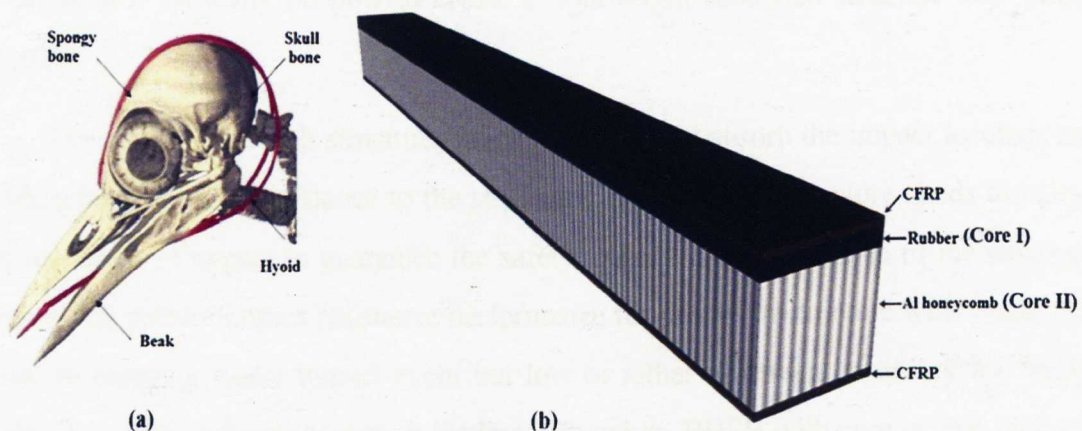


Figure 1.3. a) Head configuration of woodpecker and b) Bioinspired sandwich beam with honeycomb core (Sabah, Kueh and Al-Fasih, 2018)

The BHSB with two cores can enhance the resistance to impact but the capability of its impact resistance is still an unknown. Therefore, Sabah, Kueh, and Al-Fasih (2018) compared the effect of low-velocity impact toward conventional sandwich beam with honeycomb core (HSB) and bio-inspired sandwich beam with honeycomb core (BHSB). Sabah, Kueh, and Al-Fasih (2018) conducted investigation experimentally and numerically with a good result showing that BHSB is 5 times better than HSB as regarding to the overall impact resistance behavior. HSB is made of two carbon fibre reinforced plastic (CFRP) skin which is separated by aluminium honeycomb core. The unique properties of the cores made of honeycomb and solid viscoelastic materials can fulfill the design criteria.

1.2 Problem Statement

The previous studies on the influence of geometrical change of sandwich structure proved the impact efficiency of a sandwich structure is affected by the core and face thicknesses, curvature angle, spacing between core plate, core length, core cell wall thickness and immediate layer of the core. Sandwich structure is exposed to a succession of impacts during lifespan. Therefore, high resistance and high strength sandwich structure is needed. The problem is basically on how to create a lightweight sandwich structure with strong properties.

The core in sandwich structures helps to spread and absorb the impact loadings and provide a better impact resistance to the structure. The sandwich structure needs to have a good resistance to impact to guarantee the safety, quality and the lifespan of the structure. However, the current impact resistance performance for sandwich structure with single core is good in resisting single impact event but low or rather unknown capability for further functionality when subjecting to such loading. Therefore, BHSB with core in arch shape of 36° angle is proposed for this study as the arch shape can handle high loading as compared to flat shape and the arch shape reacts to the impact with a smaller peak displacement than flat shape.

Hence, this study is conducted to evaluate the effect of geometrical change such as core thickness and leg span of core I which is solid hot melt adhesive (HMA) on the impact behavior of the sandwich beam. The reason of studying the effect of core thickness is because no much studies evaluated the how the impact response of sandwich structure was influenced by core thickness under low velocity impact loadings. Through changing the core thickness, the ability to obtain interesting properties and desired performance is almost possible. Thicker core is better choice as it has higher impact resistance and absorbs higher energy. The effects of leg span on the efficiency of sandwich structure is studied as none of studies have been conducted on the effect of leg span and arch shape sandwich beam will offer a higher impact resistance structure.

1.3 Aims and Objectives

This study is conducted:

- To develop a composite sandwich beam finite element model under impact loading.
- To numerically examine the impact behavior of the sandwich beam due to varying core thickness and arch core leg span.
- To compute the impact efficiency of the sandwich beam due to varying core thickness and arch core leg span.

1.4 Scope of Study

The scopes of study are as shown below:

- I. The sandwich beam is a C-clamp supported at two ends.
- II. Only one impact energy of 7.28J is applied perpendicularly at the centre of the sandwich.
- III. There are two core and one skin are used in the sandwich beam.